

Single Supply Temperature Sensing with Thermocouples

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INTRODUCTION

There is a variety of temperature sensors on the market all of which meet specific application needs. The most common sensors used to solve these application problems include the thermocouple, Resistive Temperature Detector (RTD), Thermistor, and silicon based sensors. For an overview and comparison of these sensors, refer to Microchip's AN679, "Temperature Sensing Technologies".

This application note focuses on circuit solutions that use thermocouples in the design. The signal conditioning path for the thermocouple system will be discussed in this application note followed by complete application circuits.

THERMOCOUPLE OVERVIEW

Thermocouples are constructed of two dissimilar metals such as Chromel and Constantan (Type E) or Nicrosil and Nisil (Type N). The two dissimilar metals are bonded together on one end of both wires with a weld

bead. This bead is exposed to the thermal environment of interest. If there is a temperature difference between the bead and the other end of the thermocouple wires, a voltage will appear between the two wires at the end where the wires are not soldered together. This voltage is commonly called the thermocouple's Electromotive Force (EMF) voltage. This EMF voltage changes with temperature without any current or voltage excitation. If the difference in temperature between the two ends (the weld bead versus the unsoldered ends) of the thermocouple changes, the EMF voltage will change as well.

There are as many varieties of thermocouples as there are metals, but some combinations work better than others. The list of thermocouples shown in Table 1 are most typically used in industry. Their behaviors have been standardized by the National Institute of Standards and Technology (NIST). The particular document from this organization that is pertinent to thermocouples is the NIST Monograph 175, "Temperature-Electromotive Force Reference Functions and Tables for the Letter-Designated Thermocouple Types Based on the ITS-90". Manufacturers use these standards to qualify the thermocouples that they ship.

| Thermocouple Type | Conductors | Temperature range (°C) | Seebeck Coefficient (@ 20°C) | Application Environments |
|-------------------|---|------------------------|------------------------------|-----------------------------------|
| E | Chromel (+) Constantan (-) | -200 to 900 | 62µV/°C | oxidizing, inert, vacuum |
| J | Iron (+) Constantan (-) | 0 to 760 | 51µV/°C | vacuum, oxidizing reducing, inert |
| T | Copper (+) Constantan (-) | -200 to 371 | 40µV/°C | corrosive, moist, subzero |
| K | Chromel (+) Alumel (-) | -200 to 1260 | 40µV/°C | completely inert |
| N | Nicrosil (+) Nisil (-) | 0 to 1260 | 27µV/°C | oxidizing |
| B | Platinum (30% Rhodium) (+) Platinum (6% Rhodium) (-) | 0 to 1820 | 1µV/°C | oxidizing, inert |
| S | Platinum (10% Rhodium) (+) Platinum (-) | 0 to 1480 | 7µV/°C | oxidizing, inert |
| R | Platinum (13% Rhodium) (+) Platinum (-) | 0 to 1480 | 7µV/°C | oxidizing, inert |

TABLE 1: Common thermocouple types—The most common thermocouple types are shown with their standardized material and performance specifications. These thermocouple types are fully characterized by the American Society for Testing and Materials (ASTM) and specified in IST-90 units per NIST Monograph 175.

This style of temperature sensor offers distinct advantages over other types, such as the RTD, Thermistor or Silicon sensors. As stated before, the sensor does not require any electrical excitation, such as a voltage or current source.

The price of thermocouples varies dependent on the purity of the metals, integrity of the weld bead and quality of the wire insulation. Regardless, thermocouples are relatively inexpensive as compared to other varieties of temperature sensors.

The thermocouple is one of the few sensors that can withstand hostile environments. The element is capable of maintaining its integrity over a wide temperature range as well as withstanding corrosive or toxic atmospheres. It is also resilient to rough handling. This is mostly a consequence of the heavier gages of wire used with the thermocouples construction.

The temperature ranges of the thermocouples included in Table 1 vary depending on the types of metals that are used. These ranges are also shown graphically in Figure 1. All of the voltages shown in Figure 1 are referenced to 0°C.

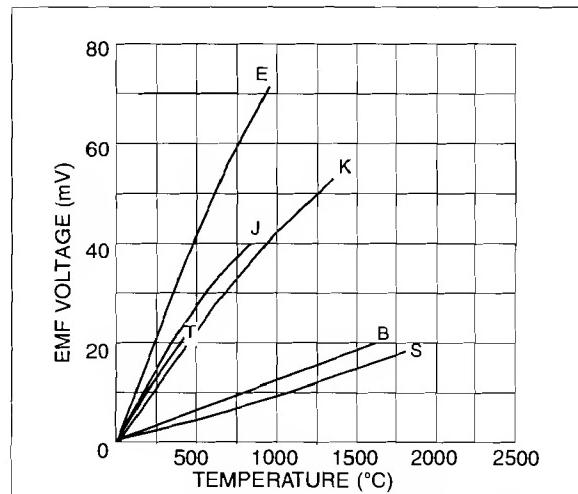


FIGURE 1: EMF voltage of various thermocouples versus temperature

Thermocouples produce a voltage that ranges from nano volts to tens of millivolts. This voltage is repeatable, but non-linear. Although this can be seen to a certain degree in Figure 1, Figure 2 does a better job of illustrating the non-linearity of the thermocouple. In Figure 2, the first derivative of the EMF voltage versus temperature is shown. This first derivative at a specified temperature is called the Seebeck Coefficient. The Seebeck Coefficient is a linearized estimate of the temperature drift of the thermocouple's bead over a small temperature range. Since all thermocouples are non-linear, the value of this coefficient changes with specified temperature. This coefficient is used when designing the hardware portion of the thermocouple system that senses the absolute reference temperature. The design and use of the absolute temperature reference will be discussed later in this application note.

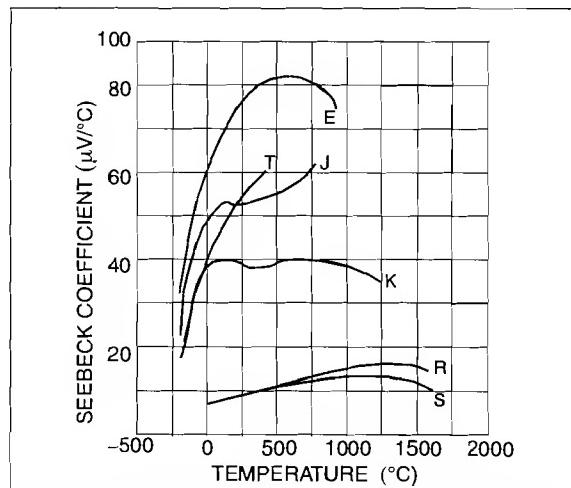


FIGURE 2: Seebeck coefficient of various thermocouples versus temperature

From Figure 1, it can be summarized that the EMF voltage of a thermocouple is extremely small (millivolts). Additionally, Figure 2 illustrates that the change of the EMF voltage per degree C is also small ($\mu\text{V}/\text{C}$). Consequently, the signal conditioning portion of the electronics requires an analog gain stage. In addition, the voltage that a thermocouple produces represents the temperature difference between the weld bead and the other end of the wires. If an absolute temperature measurement (as opposed to relative) is required, a portion of the thermocouple signal conditioning electronics must be dedicated to establishing a temperature reference.

A summary of the thermocouple's advantages and disadvantages are listed in Table 2.

| ADVANTAGES | DISADVANTAGES |
|---------------------------|--------------------------------------|
| No Excitation Required | Non-Linear |
| Inexpensive | Needs Absolute Temperature Reference |
| Wide Variety of Materials | Small Voltage Output Signals |
| Wide Temperature Ranges | |
| Very Rugged | |

TABLE 2: Thermocouple Advantages and Disadvantages

THERMOCOUPLE SIGNAL CONDITIONING PATH

The signal conditioning signal path of the thermocouple circuit is illustrated in Figure 3. The elements of the path include the thermocouple, reference temperature junction, analog gain cell, Analog-to-Digital (A/D) Converter and the linearization block. Thermocouple 1 is the thermocouple that is at the site of the temperature measurement. Thermocouple 2 and 3 are a consequence of the wires of Thermocouple 1 connecting to the copper traces of the PCB.

The remainder of this application note will be devoted to solving the reference temperature, signal gain and A/D conversion issues. Linearization issues associated with thermocouples will also be discussed.

DESIGNING THE REFERENCE TEMPERATURE SENSOR

An absolute temperature reference is required in most thermocouple applications. This is used to remove the EMF error voltage that is created by thermocouples 2 and 3 in Figure 3. The two metals of these thermocouples come from the temperature sensing element (Thermocouple 1) and the copper traces of the PCB. The isothermal block in Figure 3 is constructed so that the Thermocouples 2 and 3 are kept at the same temperature as the absolute temperature sensing device. These elements can be kept at the same temperature by keeping the circuitry in a compact area, analyzing the board for possible hot spots, and identifying thermal hot spots in the equipment enclosure. With this configuration, the known temperature of the copper junctions can be used to determine the actual temperature of the thermocouple bead.

In Figure 3, the absolute reference temperature is sensed at the isothermal block, and then subtracted from the signal path. This is a hardware implementation. Alternatively, the absolute reference temperature can be sensed and subtracted in firmware. The hardware solution can be designed to be relatively error free as will be discussed later. The firmware correction can be more accurate because of the computing power of the processor. The trade-off for this type of calibration is computing time.

The relationship between the thermocouple bead temperature and zero degrees C is published in the form of look-up tables or coefficients of polynomials in the NIST publication mentioned earlier. If the absolute temperature of thermocouple 2 and 3 (Figure 3) are known, the actual temperature at the test sight (Thermocouple 1) can be measured and then calculated.

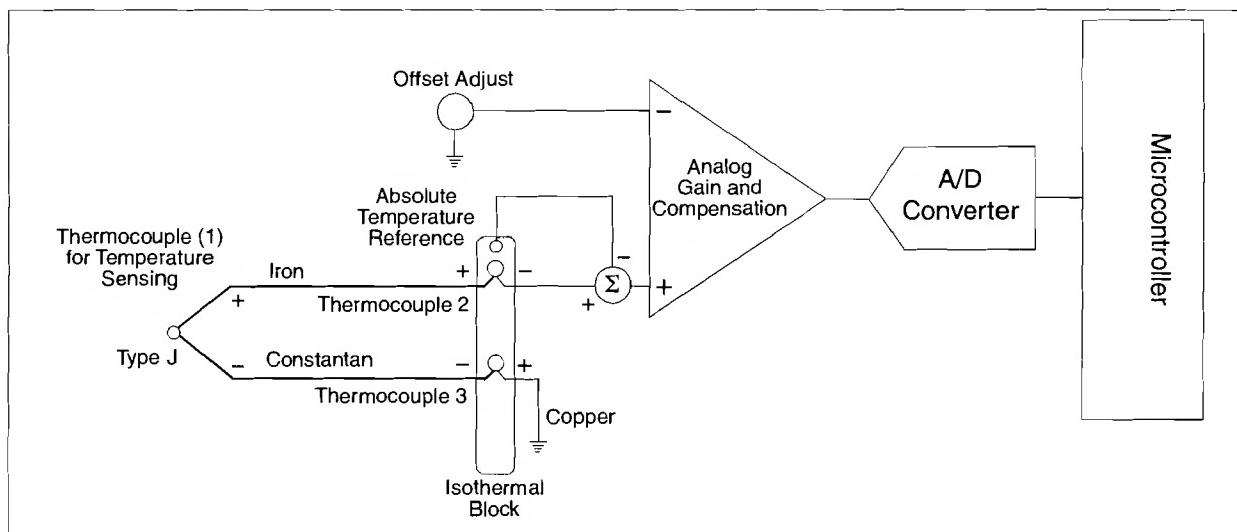


FIGURE 3: The thermocouple signal path starts with the thermocouple which is connected to the copper traces of the PCB on the isothermal block. The signal path then continues on to a differentiating circuit that subtracts the temperature of the isothermal block from the thermocouple's temperature. After this signal is digitized, a microcontroller uses the digital word from the temperature sensing circuit for further processing.

ERROR CORRECTION WITH HARDWARE IMPLEMENTATIONS

Many techniques can be used to sense the reference temperature on the isothermal block; five of which are discussed here. The first example uses a second thermocouple. It is used to sense ambient at the copper connection and configured to normalize the resultant voltage to an assignable temperature. As a second example, a standard diode is used to sense the absolute temperature of the isothermal block. This is done by using the negative temperature coefficient of $-2.2\text{mV}^{\circ}\text{C}$ characteristic of the diode. Thirdly, a thermistor temperature sensor is shown as the reference temperature device. As with the diode, the thermistor has a negative temperature coefficient. The thermistor is a more challenging to use because of its non-linear tendencies, however, the price is right. Another technique discusses an RTD as the reference temperature sensor. These sensors are best suited for precision circuits. And finally, the integrated silicon temperature sensor is briefly discussed.

Using a Second Thermocouple

A second thermocouple can be used to remove the error contribution of all of the thermocouples in the circuit. A circuit that uses this technique is shown in Figure 4.

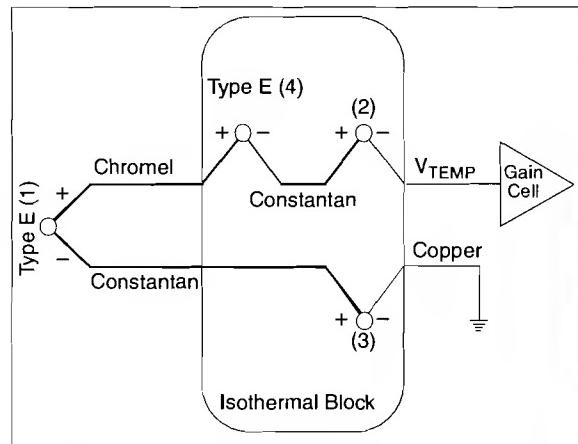


FIGURE 4: A second temperature reference can be created by using a second thermocouple.

In this circuit example, a Type E thermocouple is chosen to sense the unknown temperature. The Type E thermocouple is constructed of Chromel (a combination of Nickel and Chromium) on its positive side and Constantan on its negative side. A second Type E thermocouple is included in the circuit. It is positioned on the isothermal block and installed between the first thermocouple and the signal conditioning circuit. The polarity of the two Type E thermocouples is critical so that the Constantan on both of the thermocouples are connected together.

From this circuit configuration, two additional thermocouples are built, both of which are constructed with chromel and copper. These two thermocouples are opposing each other in the circuit. If both of these newly constructed thermocouples are at the same temperature, they will cancel each other's temperature induced errors.

The two remaining Type E thermocouples generate the appropriate EMF voltage that identifies the temperature at the sight of the first thermocouple.

This design technique is ideal for instances where the temperature of the isothermal block has large variations or the first derivative of voltage versus temperature of the selected thermocouple has a sharp slope (see Figure 2). Thermocouples that fit into this category in the temperature range from 0°C to 70°C are Type T and Type E.

The error calculation for this compensation scheme is:

$$V_{TEMP} = +EMF_3 + EMF_1 - EMF_4 - EMF_2$$

where

EMF_1 is the voltage drop across the Type E thermocouple at the test measurement site.

EMF_2 is the voltage drop across a Copper/Constantan thermocouple, where the copper metal is actually a PCB trace.

EMF_3 is the voltage drop across a Copper/Constantan thermocouple, where the copper metal is actually a PCB trace.

EMF_4 is the voltage drop across a Type E thermocouple on the Isothermal Block.

V_{TEMP} is the equivalent EMF voltage of a Type E thermocouple, #1, referenced to 0°C .

The temperature reference circuitry is configured to track the change in the Seebeck Coefficient fairly accurately. The dominating errors with this circuit will occur as a consequence of less than ideal performance of the Type E thermocouples, variations in the purity of the various metals, and an inconsistency in the temperature across the isothermal block.

Diode Temperature Sensing

Diodes are useful temperature sensing devices where high precision is not a requirement. Given a constant current excitation, standard diodes, such as the IN4148, have a voltage change with temperature of approximately $-2.2\text{mV}^{\circ}\text{C}$. These types of diodes will provide fairly linear voltage versus temperature performance. However, from part to part they may have variations in the absolute voltage drop across the diode as well as temperature drift.

This type of linearity is not well suited for thermocouples with wide variations in their Seebeck Coefficients over the temperature range of the isothermal block (referring to Figure 2). If there are wide variations with the isothermal block temperature, Type K, J, R and S

thermocouples may be best suited for the application. If the application requires more precision in terms of linearity and repeatability from part to part than an off-the-shelf diode, the MTS102, MTS103 or MTS105 from Motorola® can be substituted.

A circuit that uses a diode as an absolute temperature sensor is shown in Figure 5. A voltage reference is used in series with a resistor to excite the diode. The diode change with temperature has a negative coefficient, however, the magnitude of this change is much higher than the change of the collective thermocouple junctions on the isothermal block. This problem is solved by putting two series resistors in parallel with the diode. In this manner, the change of $-2.2\text{mV}/^\circ\text{C}$ of the diode is attenuated to the Seebeck Coefficient of the thermocouple on the isothermal block. The Seebeck Coefficient of the thermocouples on the isothermal block are also equal to the Seebeck Coefficient (at isothermal block temperature) of the thermocouple that is being used at the test site. Table 3 has some recommended resistance values for various thermocouple types and excitation voltages.

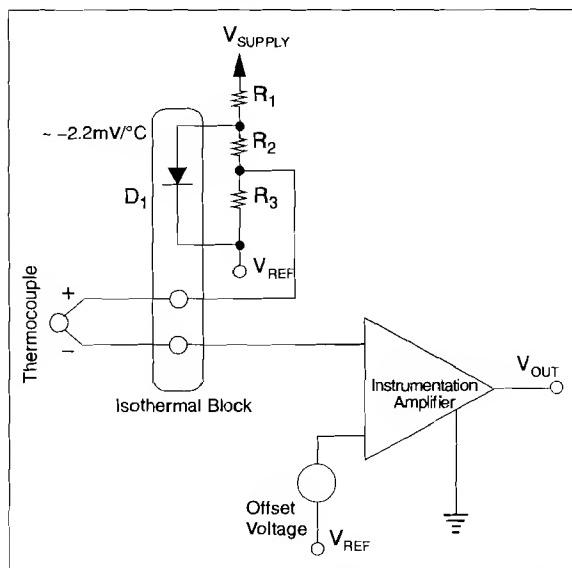


FIGURE 5: A diode can also be used in a hardware solution to zero out the temperature errors from the isothermal block.

This circuit appears to provide a voltage excitation for the diode. This is true, however, the ratio of the voltage excitation to the changes in voltage drop changes with temperature across the diode minimize linearity errors.

Of the three voltage references chosen in Table 3, the 10V reference provides the most linear results. It might also be noticed that changes in the reference voltage will also change the current through the diode. This being the case, a precision voltage reference is recommended for higher accuracy application requirements.

| Thermocouple Type | Seebeck Coefficient (@20°C) | V _{REF} (V) | R ₁ (Ω) | R ₂ (Ω) | R ₃ (Ω) |
|-------------------|-----------------------------|----------------------|--------------------|--------------------|--------------------|
| J | 51μV/°C | 4.096 | 9.76k | 4.22k | 100 |
| J | 51μV/°C | 5.0 | 12.1k | 4.22k | 100 |
| J | 51μV/°C | 10.0 | 27k | 4.22k | 100 |
| K | 40μV/°C | 4.096 | 9.76k | 5.36k | 100 |
| K | 40μV/°C | 5.0 | 12.1k | 5.36k | 100 |
| K | 40μV/°C | 10.0 | 27k | 5.36k | 100 |
| R | 7μV/°C | 4.096 | 9.76k | 31.6k | 100 |
| R | 7μV/°C | 5.0 | 12.1k | 31.6k | 100 |
| R | 7μV/°C | 10.0 | 27k | 31.6k | 100 |
| S | 7μV/°C | 4.096 | 9.76k | 31.6k | 100 |
| S | 7μV/°C | 5.0 | 12.1k | 31.6k | 100 |
| S | 7μV/°C | 10.0 | 27k | 31.6k | 100 |

TABLE 3: Recommended resistors and voltage references versus thermocouples for the circuit shown in Figure 5

Thermistor Circuits

Thermistors are resistive devices that have a Negative Temperature Coefficient (NTC). These inexpensive sensors are ideal for moderate precision thermocouple sensing circuits when some or all of the non-linearity of the thermistor is removed from the equation.

The NTC thermistor's non-linearity can be calibrated out with firmware or hardware techniques. The firmware techniques are more accurate, however, hardware techniques are usually more than adequate. Details on these linearity issues of thermistors are discussed in Microchip's AN685, "Thermistors in Single Supply Temperature Sensing Circuits".

Figure 6 shows a thermistor in series with a equivalent resistor and voltage excitation. In this circuit, the change in voltage with temperature is $\sim -25\text{mV}^{\circ}\text{C}$. This temperature coefficient is too high. A resistor divider (R_1 and R_2 in Figure 6) can easily provide the required temperature coefficient dependent on the thermocouple type.

This type of voltage excitation does have fairly linear operation over a limited temperature range (0°C to 50°C). Taking advantage of this linear region reduces firmware calibration overhead significantly.

Alternatively, the NTC thermistor can be excited with a current source. Low level current sources, such as $20\mu\text{A}$ are usually recommended which minimizes self heating problems. A thermistor that is operated with current firmware excitation has a fairly non-linear output. With this type of circuit, firmware calibration would be needed. Although the firmware calibration is somewhat cumbersome, this type of excitation scheme can be more accurate.

Figure 7 compares the linearity of the thermistor with the current excitation configuration to a voltage excitation scheme shown in Figure 6.

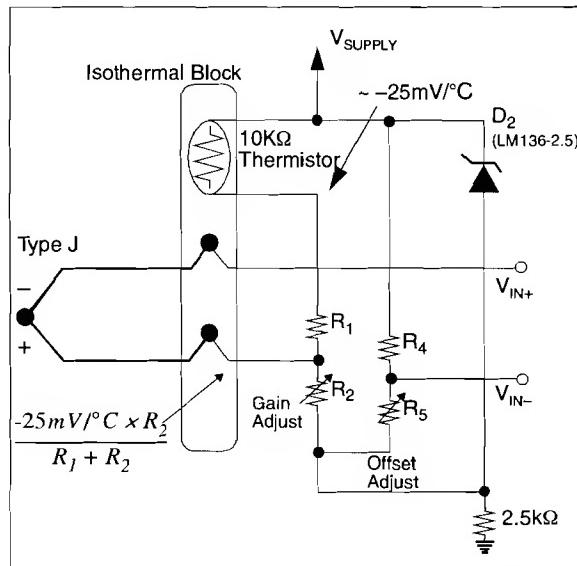


FIGURE 6: As a third method, a thermistor is used to sense the temperature of the isothermal block. In this circuit, the isothermal block error is eliminated in hardware.

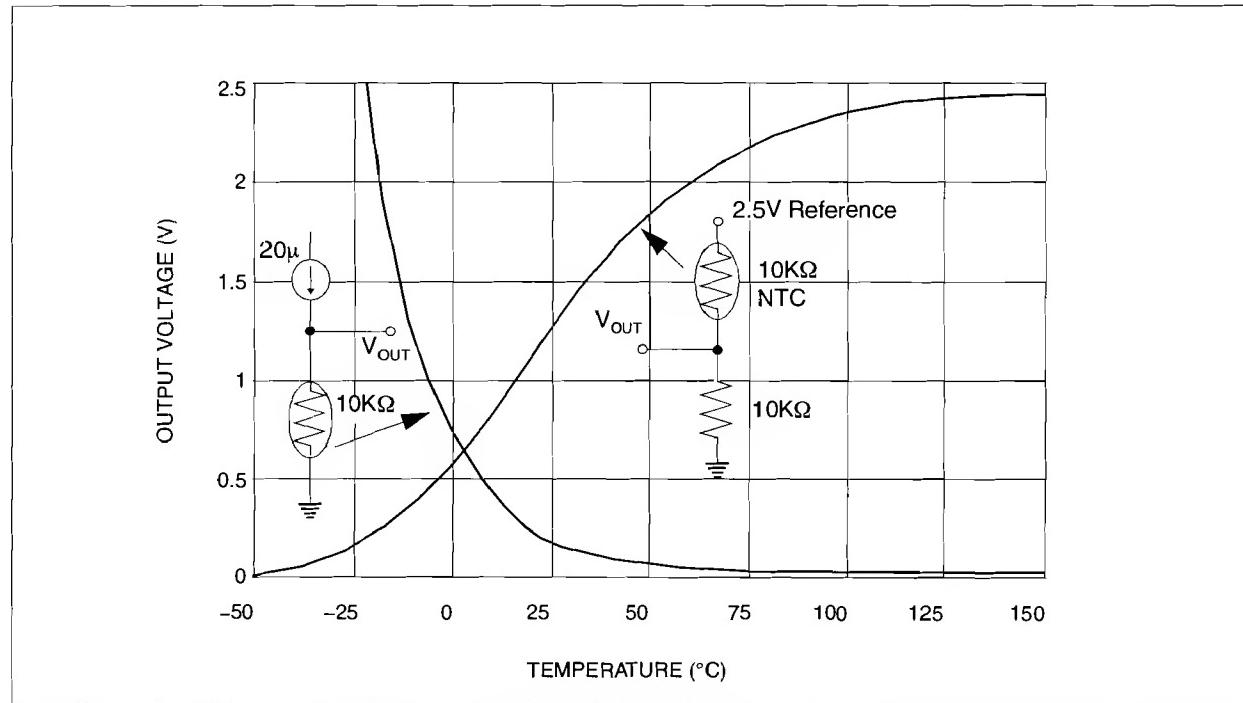


FIGURE 7: The Thermistor in Figure 6 requires linearization. This can be accomplished by using the Thermistor in parallel with a standard resistor.

RTD Sensor Circuits

Typically, an RTD would be used on the isothermal block if high precision is desired. The RTD element is nearly linear, consequently, employing linearization algorithms for the RTD is usually not required. The most effective way to get good performance from an RTD is to excite it with current. Both Figure 8 and Figure 9 show circuits that can be used for this purpose.

In Figure 8, a precision current reference is gained by the combination of R_1 , R_2 , J_1 , U_1 and U_2 . U_2 generates a $200\mu\text{A}$ precision current source. That current is pulled across R_1 forming a voltage drop for the power supply down to the non-inverting input of U_1 . U_1 is used to isolate R_1 from R_2 , while translating the voltage drop across R_1 to R_2 . In this manner, the $200\mu\text{A}$ current from U_2 is gained by the ratio of R_1/R_2 . J_1 is used to allow the voltage at the top of the RTD element to float dependent on its resistance changes with temperature. The RTD element should be sensed differentially. The voltage across this differential output is proportional to absolute temperature.

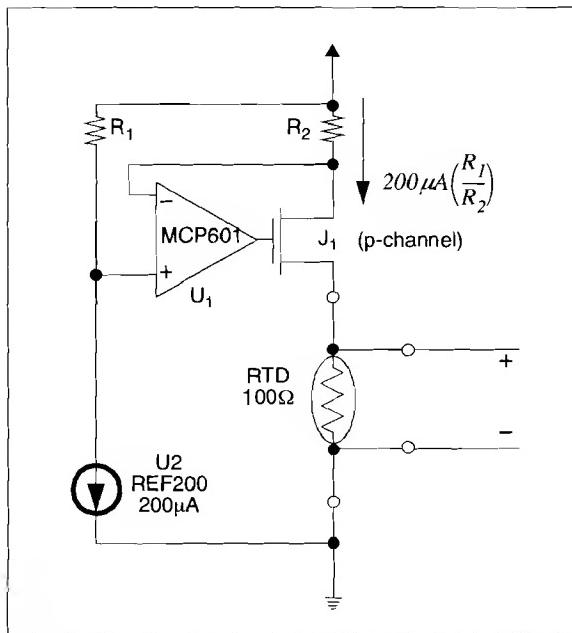


FIGURE 8: An 4-wire RTD can be used to sense the temperature of the isothermal block. RTDs require a precision current excitation as shown here.

In Figure 9, a voltage reference is used to generate a 1mA current source for the RTD element. The advantage of this configuration is that the voltage reference can be used elsewhere, allowing ratiometric calibration techniques in other areas of the circuit.

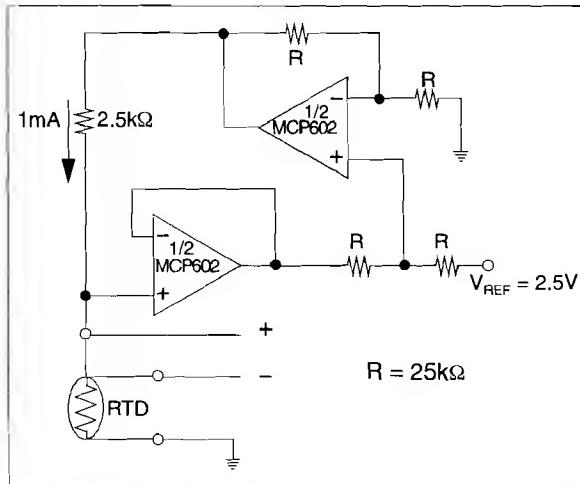


FIGURE 9: 3-wire RTD current excitation is generated with a precision voltage reference.

The RTD sensor is best suited for situations where precision is critical. Both of the RTD circuits (Figure 8 and Figure 9) will output a voltage that is fairly linear and proportional to temperature. This voltage is then used by the microcontroller to convert the absolute temperature reading of the isothermal block back to the equivalent EMF voltage. This can be performed by the microcontroller with a look-up table or a polynomial calculation for higher accuracy. This EMF voltage is then subtracted from the voltage measured across the sensor/isothermal block combination. In this manner, the errors from the temperature at the isothermal block are removed.

For more information about RTD circuits, refer to Microchip's AN687, "Precision Temperature Sensing with RTD Circuits".

Silicon Sensor

Silicon temperature sensors are differentiated from the simple diode because of their complexity (see Figure 10). A silicon temperature sensor is an integrated circuit that uses the diode as a basic temperature sensing building block. It conditions the temperature response internally and provides a usable output such as 0 to 5V output, digital 8 or 12 bit word, or temperature-to-frequency output.

The output of this type of device is used by the processor to remove the isothermal block errors.

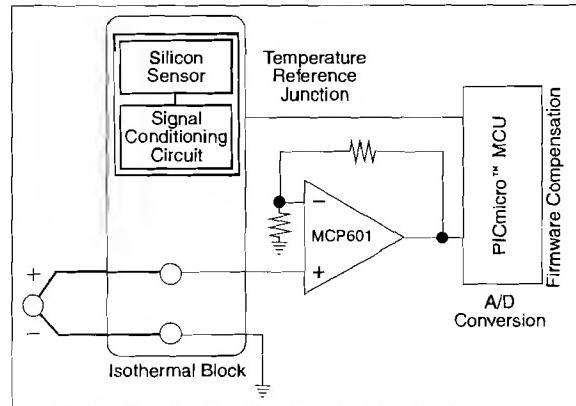


FIGURE 10: Silicon sensors are also useful for isothermal block temperature sensing. These type of devices only sense the temperature and do not implement any error correction in hardware.

SIGNAL CONDITIONING CIRCUITS

Once the reference temperature of the isothermal block is known, the temperature at the bead of the thermocouple can be determined. This is done by taking the EMF voltage, subtracting isothermal block errors, and determining the temperature through look-up tables or linearization equations. The EMF voltage must be digitized in order to easily perform these operations. Prior to the A/D conversion process, the low level voltage at the output of the thermocouple must be gained.

This is typically done with an instrumentation amplifier or a operational amplifier in a high gain configuration. An instrumentation amplifier uses several operational amplifiers and is configured to have a electrically equivalent differential inputs, high input impedance, potentially high gain, and good common-mode rejection. Of these four attributes, the first three are most useful for thermocouple applications.

Single supply configurations of instrumentation amplifiers are shown in Figure 11 and Figure 12. In Figure 11, three operation amplifier are used along with a selection of resistors. The circuit gain in Figure 11 can be controlled with R_G .

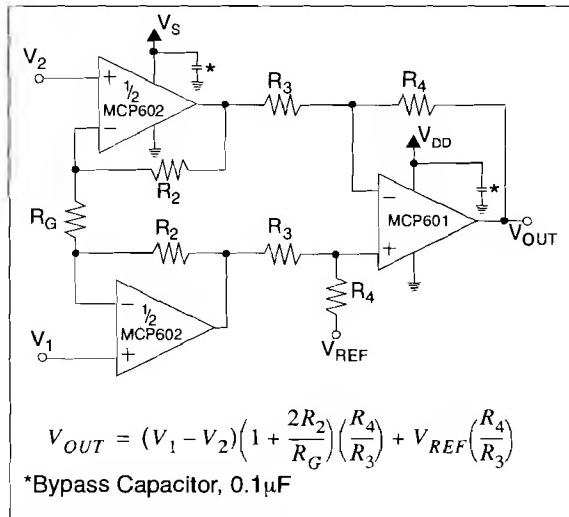


FIGURE 11: Instrumentation amplifier using three operational amplifiers

In Figure 12, an instrumentation amplifier is built using two amplifiers. Once again the gain is easily adjusted with R_G in the circuit.

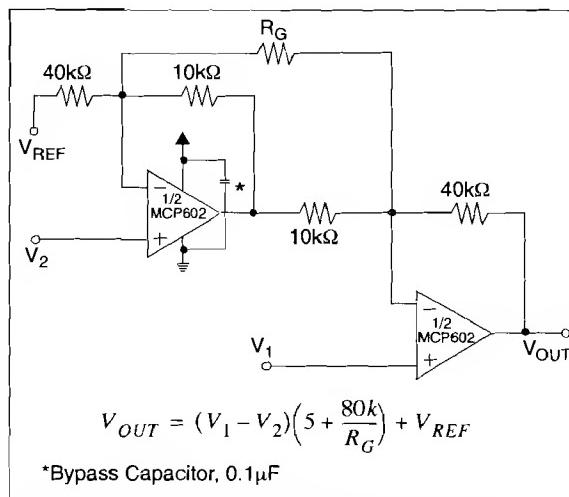


FIGURE 12: Instrumentation amplifier using two operational amplifiers

More details concerning the operation of Figure 11 and Figure 12 circuit configurations can be found in Microchip's AN682, "Using Single Supply Operational Amplifiers in Embedded Systems".

Finally, Figure 13 shows an circuit configuration using a single operational amplifier in an non-inverting gain.

These operational amplifier circuits will be used in the signal conditioning portion of the following thermocouple circuits.

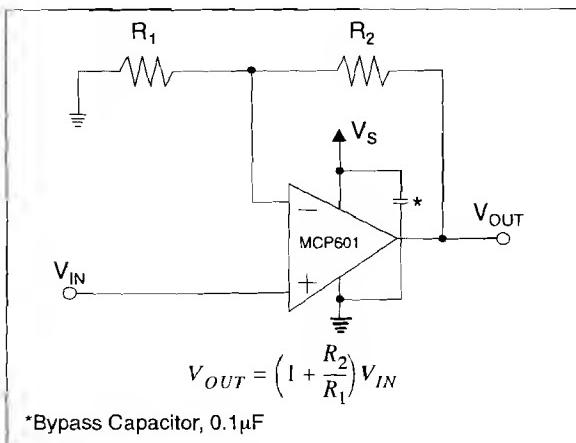


FIGURE 13-A A single operational amplifier can be configured for analog gain.

THERMOCOUPLE CIRCUITS VERSUS ACCURACY

There are three types of thermocouple sensing systems in this section. The first circuit is designed to sense a threshold temperature. The second circuit will provide up to 8 bits of accuracy. This circuit accuracy can be improved by adding a higher resolution A/D Converter to the circuit, as shown in the third sensing system.

Threshold Temperature Sensing

A thermocouple can be used to sense threshold temperatures. This is particularly useful in industrial applications where high temperature processes need to be limited. The circuit to implement this type of function is shown in Figure 14. The threshold temperature sensing circuit in this figure combines the building blocks from Figure 4 and Figure 13.

This circuit is designed for simplicity. Consequently, all of the isothermal block error correction is performed in hardware. The Type E thermocouple is chosen for this circuit because of its high EMF voltage at high temperatures. This makes it easier to separate the real signal from background noise. Since the output of the isothermal block is single ended, the amplifier circuit in Figure 13 is used. In the event that there is a great deal of ambient or electrical noise, an instrumentation amplifier would serve this application better.

The EMF voltage of the thermocouple is calibrated across the isothermal block with a second thermocouple. This voltage is then gained by a single supply amplifier in a non-inverting configuration. The gain on the amplifier is adjustable by changing the ratio of R_2 and R_1 . In this case the signal is gained by 47.3V/V using a MCP601, single supply, CMOS operational amplifier. This gain was selected to provide a 2.5V output to the amplifier for a 700°C mid-scale measurement.

The microcontroller comparator can be programmed to compare between 1.25V and 3.75V with increments of $V_{DD}/32$ (LSB size of 156.25mV). This is done by configuring the CMCON register of the PIC16C62X to $CxOUT = 0$ and $CM<2:0> = 010$. Additionally, the voltage reference to the comparator is changed in the VRCON register. The initial settings for this register is $VREN = 1$ and $VRR = 0$. The processor can then cycle through the VRCON register $VR<3:0>$ for a total of 16 different voltage reference settings for comparisons to the input signal from the MCP601 operational amplifier.

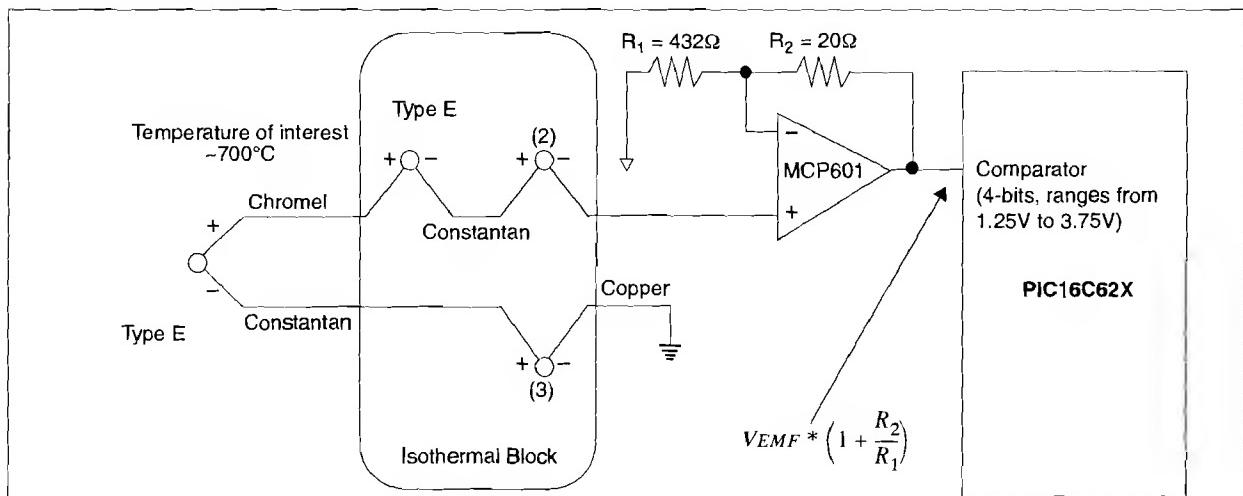


FIGURE 14: This circuit can be used to determine temperature thresholds. With calibration, the circuit is accurate to four bits.

| °C | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|-----|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 500 | 37.005 | 37.815 | 38.624 | 39.434 | 40.243 | 41.052 | 41.862 | 42.671 | 43.479 | 44.286 | 450.93 |
| 600 | 45.093 | 45.900 | 46.705 | 47.509 | 48.313 | 49.116 | 49.917 | 50.718 | 51.517 | 52.315 | 53.112 |
| 700 | 53.112 | 53.908 | 54.709 | 55.497 | 56.289 | 57.080 | 57.870 | 58.659 | 58.446 | 60.232 | 61.017 |
| 800 | 61.017 | 61.801 | 62.583 | 63.364 | 64.144 | 64.922 | 65.698 | 66.473 | 67.246 | 68.017 | 68.787 |
| 900 | 68.787 | 69.554 | 70.319 | 71.082 | 71.844 | 72.603 | 73.360 | 74.115 | 74.869 | 75.621 | 76.373 |

TABLE 4: Type E thermocouple look-up table. All values in the tables are in millivolts.

A look-up table for the millivolts to 500°C to 1000°C for the Type E thermocouple is provided in Table 4. The temperature at the test sight is found by dividing the output voltage of the amplifier by 47.3 and using the look-up table to estimate the actual temperature. AN566, "Implementing a Table Read" can be used in this application to program the PICmicro® microcontroller.

Measurement errors (referred to the thermocouple) in this circuit come from, the offset voltage of the operational amplifier (+/-2mV) and the comparator LSB size (+/-1.65mV). Negligible error contributions come from the look-up table resolution, resistors and power supply variations.

Given the errors above, the accuracy of the comparison in this circuit is ~ +/-35°C over a nominal temperature range of 367.7°C to 992.6°C. This error can be calibrated out. The temperature thresholds for the various settings of VR<3:0> of the VRCON register is summarized in Table 5.

This accuracy can be improved by using an amplifier with less initial offset voltage or an A/D conversion with more bits.

All of the temperature calibration work in this circuit is performed in hardware. Linearization and temperature accuracy are performed in firmware with the look-up table above.

| VR<3:0> | Comparator Reference | Nominal Temperature Threshold |
|---------|----------------------|-------------------------------|
| 0000 | 1.25V | 368.4°C |
| 0001 | 1.40625V | 409.8°C |
| 0010 | 1.5625V | 450.9°C |
| 0011 | 1.71875V | 491.7°C |
| 0100 | 1.875V | 532.6°C |
| 0101 | 2.03125V | 573.4°C |
| 0110 | 2.1875V | 614.3°C |
| 0111 | 2.34375V | 655.4°C |
| 1000 | 2.5V | 696.8°C |
| 1001 | 2.65625V | 738.3°C |
| 1010 | 2.8125V | 780.2°C |
| 1011 | 2.96875V | 822.3°C |
| 1100 | 3.125V | 864.8°C |
| 1101 | 3.28125V | 907.6°C |
| 1110 | 3.4375V | 950.9°C |
| 1111 | 3.59375V | 994.7°C |

TABLE 5: With a PIC16C62X controller, the comparator reference voltage is shown with the nominal temperature threshold that would be measured with the circuit in Figure 14

Temperature Sensing up to 8-bits

An eight bit accurate thermocouple circuit is achievable by using the circuit shown in Figure 15. A Type K thermocouple is chosen for this circuit because of its stable Seebeck Coefficient between 0 and 50°C. Circuits from Figure 7 and Figure 11 are used to implement the reference temperature block as well as the signal conditioning block, respectively.

The thermistor is used as the absolute temperature sensor on the isothermal block. The combination of the thermistor and the surrounding resistors perform a first order linearization of the thermistor as discussed earlier.

The non-inverting input of the instrumentation amplifier (see Figure 11) is connected to the combination of the Type K thermocouple and the thermistor error correction circuitry. The inverting input of the instrumentation

amplifier is connected to the combination of R_4 and R_5 which provide an offset adjust capability. This offset adjustment capability is not needed if the temperature sensing application starts from 0°C. However, if the temperature of interest is above a certain threshold, the offset adjust can be used to improve the dynamic range of the measurement by allowing for the full-scale range of the instrumentation amplifier and the A/D Converter to be utilized.

Assuming that the temperature range of the measurement is from 500°C to 1000°C an appropriate offset voltage at the inverting input of the instrumentation amplifier would be 43.72mV for the combination of the Type K thermocouple offset at 750°C (per Table 6) and for the thermistor absolute temperature sensing circuit at 25°C.

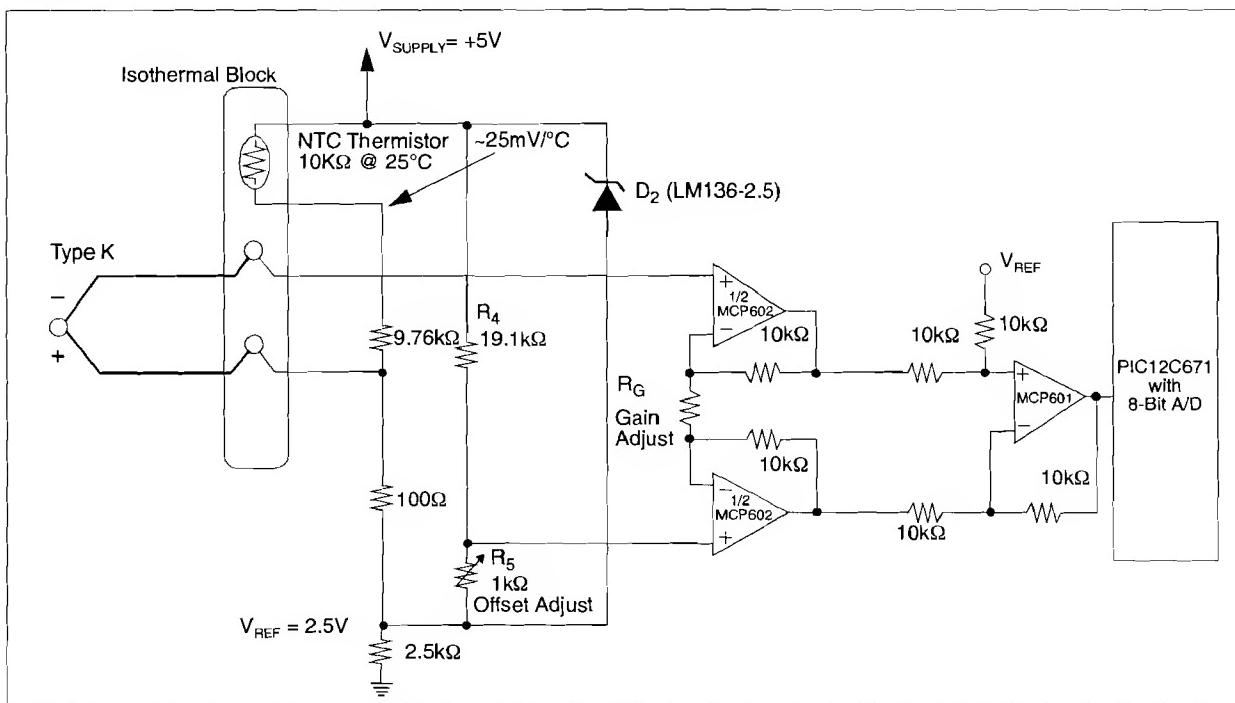


FIGURE 15: This circuit will provide 8-bit accurate temperature sensing results using a thermocouple. In this circuit, the A/D Converter is included in the PIC12C671 microcontroller.

| °C | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|-----|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 500 | 20.644 | 21.071 | 21.497 | 21.924 | 22.360 | 22.776 | 23.203 | 23.629 | 24.055 | 24.480 | 24.905 |
| 600 | 24.905 | 25.330 | 25.766 | 26.179 | 26.602 | 27.025 | 27.447 | 27.869 | 28.289 | 28.710 | 29.129 |
| 700 | 29.129 | 29.548 | 29.965 | 30.382 | 30.798 | 31.213 | 31.628 | 32.041 | 32.453 | 32.865 | 33.275 |
| 800 | 33.275 | 33.685 | 34.093 | 34.501 | 34.906 | 35.313 | 35.718 | 36.121 | 35.524 | 36.925 | 37.326 |
| 900 | 37.326 | 37.725 | 38.124 | 38.522 | 38.918 | 39.314 | 39.708 | 40.101 | 40.494 | 40.885 | 41.276 |

TABLE 6: Type K thermocouple output voltage look-up table. All values in the table are in millivolts.

Assuming that the offset has been minimized, the output range of the thermocouple circuit for an excursion from 500 °C to 1000 °C is $\Delta 20.632\text{mV}$.

The output of the instrumentation amplifier swings up to $V_{DD} - 100\text{mV}$. In this single supply, 5V environment, the output of the MCP601 operational amplifier will swing from 100mV to 4.9V.

The differential voltage swing at the inputs to the instrumentation amplifier is -17.41mV to $+16.13\text{mV}$ centered around the voltage reference of 2.5V.

Given a full-scale voltage of 33.54mV from the temperature sensing circuit, the instrumentation amplifier can be configured for a gain of 137.85V/V. This gain can easily be implemented by making R_G equal to 147Ω . This circuit is not restricted to 8-bits of accuracy. An external A/D Converter such as one of Microchip's 12-bit A/D Converter, MCP320X, can be used to further enhance the circuit's accuracy.

High Precision Temperature Sensing with a 12-bit Converter

The circuit shown in Figure 15 can be further enhanced to allow for 12-bit accuracy with the addition of a MCP3201 12-bit A/D Converter and a 4th order low pass analog filter. With this circuit, the PIC12C671 is replaced with the PIC12C509.

The analog circuit in Figure 16, remains unchanged from the design shown in Figure 15 up to the analog low pass filter. This additional low pass filter is constructed using the MCP602, CMOS dual operational amplifier. The 4th order low pass filter Butterworth design that is implemented in this circuit has a cut-off frequency of 10Hz. This cut-off frequency assumes that the sample rate of the MCP3201 is 20Hz or greater. The analog filter is used to remove the instrumentation amplifier noise, as well as the noise that may be aliased into the digital conversion from the environment. For more information about analog filter design, refer to Microchip's AN699, "Anti-Aliasing Filters for Data Acquisition Systems". The 12-bit resolution provided by the MCP3201 allows for a temperature measurement accuracy of 0.1 °C over the 500 °C to 1000 °C range of this circuit.

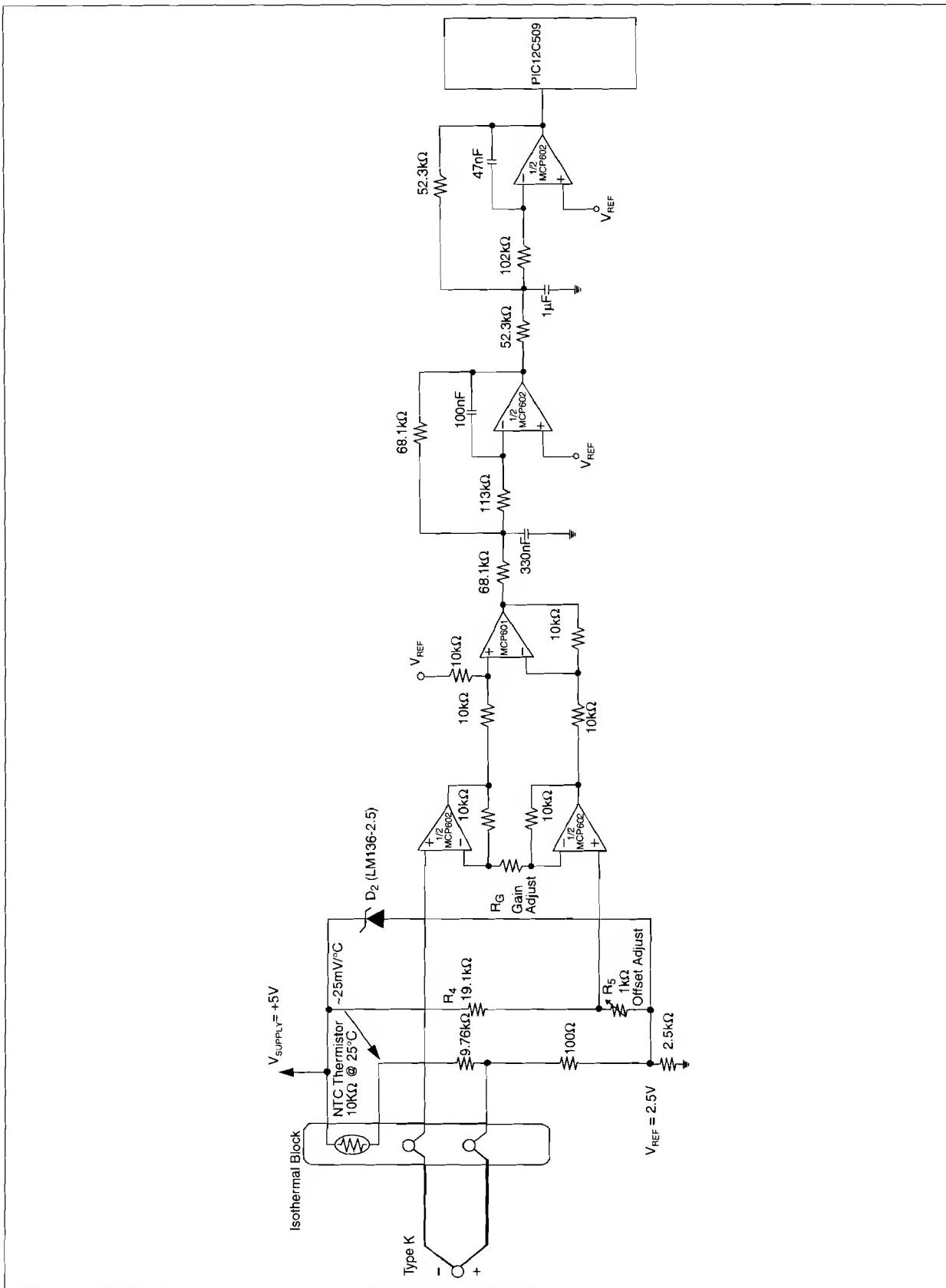


FIGURE 16: This circuit will provide 12-bit accurate temperature sensing results using a thermocouple. In this circuit, an external A/D Converter (MCP3201), is used to digitize the analog signal.

THERMOCOUPLE LINEARIZATION

Once a voltage from the absolute reference temperature sensor is digitized, the processor can implement a variety of algorithms. In the case with the circuit in Figure 15, the processor scans a simple look-up table. With this type of data, the microcontroller is left to translate the signal from the sensing element into the appropriate EMF voltage.

For high precision applications, look-up tables may not be adequate. In these cases, a multi-order polynomial can be used to generate the thermocouples temperature. The polynomial coefficients for Voltage to Temperature Conversion ($T = a_0 + a_1V + a_2V^2 + \dots + a_nV^n$) are shown in Table 7.

For further discussion concerning the firmware implementation of thermocouple linearization, refer to AN556. This application note discussed the implementation of look-up tables. Additionally, firmware is available from Microchip that provides look-up tables code to do linearization that is directly programmable into the PICmicro® microcontroller of your choice.

CONCLUSION

Thermocouples have their advantages when used in tough application problems. They are rugged and impervious to hostile environments. The voltage output of this temperature sensing element is relatively low when compared to the devices that can convert voltage signals to a digital representation. Consequently, analog gain stages are required in the circuit.

| | Thermocouple Type | | | | | |
|-----------------|-------------------|----------------|---------------|----------------|-----------------|---------------|
| | E | J | K | R | S | T |
| Range | 0° to 1000°C | 0° to 760°C | 0° to 500°C | -50° to 250°C | -50° to 250°C | 0° to 400°C |
| a ₀ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| a ₁ | 1.7057035E-2 | 1.978425E-2 | 2.508355E-2 | 1.8891380E-1 | 1.84949460E-1 | 2.592800E-2 |
| a ₂ | -2.3301759E-7 | -2.00120204E-7 | 7.860106E-8 | -9.3835290E-5 | -8.00504062E-5 | -7.602961E-7 |
| a ₃ | 6.543558E-12 | 1.036969E-11 | -2.503131E-10 | 1.3068619E-7 | 1.02237430E-7 | 4.637791E-11 |
| a ₄ | -7.3562749E-17 | -2.549687E-16 | 8.315270E-14 | -2.2703580E-10 | -1.52248592E-10 | -2.165394E-15 |
| a ₅ | -1.7896001E-21 | 3.585153E-21 | -1.228034E-17 | 3.5145659E-13 | 1.88821343E-13 | 6.048144E-20 |
| a ₆ | 8.4036165E-26 | -5.344285E-26 | 9.804036E-22 | -3.8953900E-16 | -1.59085941E-16 | -7.293422E-25 |
| a ₇ | -1.3735879E-30 | 5.099890E-31 | -4.413030E-26 | 2.8239471E-19 | 8.23027880E-20 | |
| a ₈ | 1.0629823E-35 | | 1.057734E-30 | -1.2607281E-22 | -2.34181944E-23 | |
| a ₉ | -3.2447087E-41 | | -1.052755E-35 | 3.1353611E-26 | 2.79786260E-27 | |
| a ₁₀ | | | | -3.3187769E-30 | | |
| Error | +/-0.02°C | +/-0.05°C | +/-0.05°C | +/-0.02°C | +/-0.02°C | +/-0.03°C |

TABLE 7: NIST Polynomial Coefficients of Voltage-to-temperature conversion for various thermocouple type

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